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Wide Area Monitoring & Control – Summary of Experiences with FACTS and HVDC Applications in a real-time Environment

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Wide Area Monitoring & Control – Summary of Experiences with FACTS and HVDC Applications in a real-time Environment

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1 Introduction

During the last years phasor measurement unit (PMU) based wide area monitoring systems (WAMS) have been evolved far beyond basic protection functions [1]. Today WAMS technology is seen as a powerful technology platform enabling dozens of new application in power system control and operation (e.g. [2]-[8]).

In particular, certain coordinated control functions of network controller like conventional phase angle regulators, FACTS devices or HVDC systems are enabled by WAMS. In particular against the background of increased amount of transcontinental energy transmission WAMS can be used to avoid adverse interactions between network controllers. Consequently, the WAMS technology can be seen as a platform for more secure operation of interconnected power systems. The operation of today's interconnected power systems with corridors to transmit bulk energy between different states demands the operation of the existing transmission assets at their limits. On top of the aforementioned applications, WAMS platform can be taken to setup a supervisory system that allows for new energy management functions. In particular, this applies to those areas, which are supervised by different SCADA/EMS systems within an interconnected power system.

The next step towards an overall control system is to operate the WAMS in closed loop mode in order to control network controllers. This yields a wide area control system (WACS) which is seen as a powerful concept to ensure safer and more reliable system operation even in case of multiple fast network controllers (see also [9]). Most of the application studies for WACS have been carried out on a software simulation basis, where some essential real world real-time constraints are difficult to analyze. In order to study these particular boundary conditions, a WACS has been setup within a reduced scale model of a part of the Swiss transmission grid. In addition, this model comprises fast network controllers (Unified Power Flow Controller, Phase Angle Regulators and High Voltage Direct Current Systems) which are subjected to be coordinated and controlled by means of the WACS.

This paper summarizes various application studies within a reduced scale network model for various WAMS and WACS functions. All functions can be embedded into a Three-Layer-Architecture that has been introduced in [10]. Results of corresponding lab tests will be given and discussed. They result out of a prototype implementation of typical control functions in the above mentioned laboratory environment in order to investigate the methods with respect to real-time constraints.

This paper is organized as follows. Section 2 outlines the system setup with respect to the utilized real-time simulation environment. A subset of the Swiss transmission system stations has been modeled in a reduced scale laboratory setup. Two basic configurations have been analyzed: Interconnected section of the transmission grid and – based on the same models – a topology that allows for the analysis of corridors which interfaces two areas of the ENTSO-E grid. As an overall architecture for different functions in an "overlay" power system control system a three layer approach has been taken as basis. The three layers represent the typical views on the process in power systems.

Chapter 3 gives the summary of the various application studies for WAMS and WACS based on the aforementioned real-time lab environment. Typical functions each of which representing an example of one of the three architectural control system layers are briefly described. Results of the simulation cases a presented and discussed. The application focus lies on network operation with the optimization of different network controllers.

2 System Setup

2.1 Three-Layer-Architecture

Operation of network controllers in interconnected power systems is a very complex task in three dimensions: control structure design, control objective definition and data availability. With respect to comprehensive system control all dimensions are of equal importance. Control structure design and control objective definition strongly depends on the application area. If it comes to applications in interconnected power systems a coordinated operation is of utmost importance. This underlines the need for a control system architecture avoiding adverse controller interactions while covering all time ranges of operation (e.g. [11]).

Most of the approaches have been based on the assumption of an ideal functioning of the network control system (data availability) and the existence of suitable objective functions. Today the control objectives are subjected to rapid changes. In the light of power market deregulation the power flow objectives may change from loss minimization to maximum import capacity from one operation cycle to another. Not least because the advent of PMU technology and TCP/IP based communication in substations (IEC 61850, [12]) – which will become standard for system wide communication as well – a comprehensive architecture covering the whole range of application areas is needed. One approach covering all dimension of system control is a Three-Layer-Architecture (TLA) [10] (Figure 1).

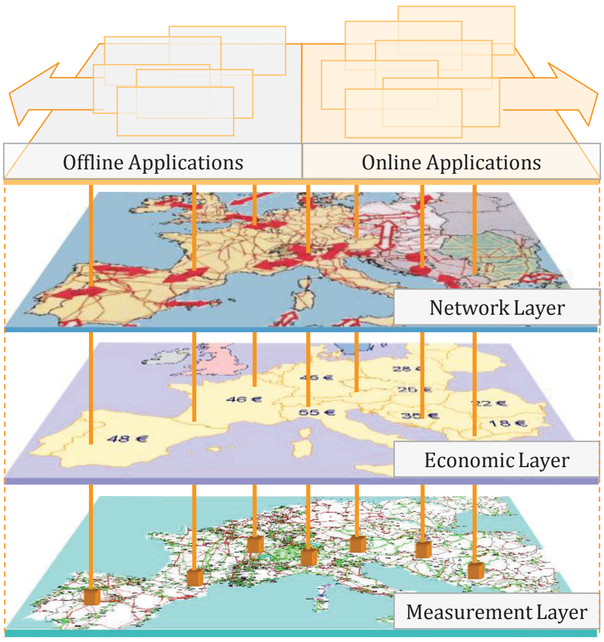


Figure 1: General concept of the Three-Layer-Architecture

The general concept of TLA is to consider the communication system (measurement layer), the system economic state (economic layer) and the network state (network layer) at the same time. While considering all three systems, time deficiencies inherent to each subsystem, can be incorporated in the controller design. Based on this all-embracing system view online and offline applications can be tuned accordingly. As a consequence, multi objective controller coordination becomes more precise.

2.2 Reduced Scale Model

This analogue simulation environment has been utilized for various WAMS and WACS application studies ([10], [13], [14]). The network model that has been built for real-time simulation represents the power grid of the region of Fribourg in Switzerland according to Figure 2. Various power electronic based network controllers (FACTS and HVDC) can be inserted into the power system. In order to study the behavior of embedded HVDC one scheme has been integrated into the network. As reference for a parallel operation, a HVDC transmission line has been integrated between Breite and Sils. This is referred to as a model of a potential DC based Swiss alpine corridor. The HVDC scheme is based on voltage source converter technology. The phase shifting transformers have been modeled by a series connected voltage source that is fed out of shunt branch. Figure 2 shows a sample setup of the network topology.

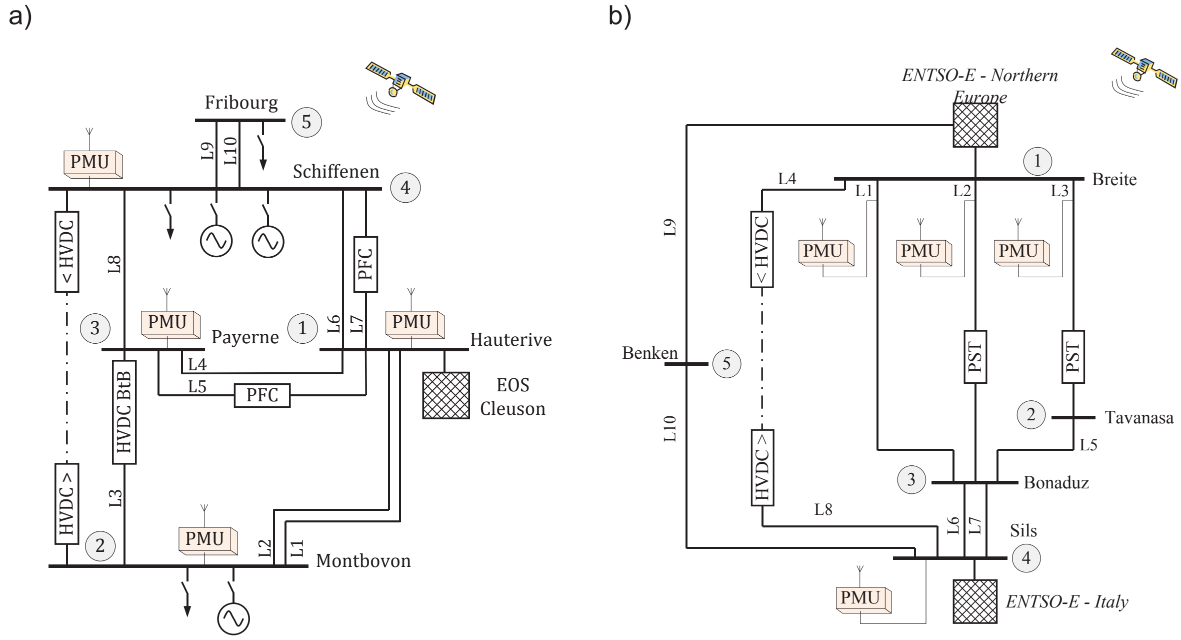


Figure 2: Sample topology of the transmission network
a) System setup for Intra-TSO-Analysis (Configuration A)
b) System setup for Inter-TSO-Analysis (Configuration B)

Configuration A has interconnections to the rest of the Swiss transmission grid whereas network configuration B comprises two interconnections to the ENTSO-E system which have been modeled as ideal network interconnections. For system studies typical faults can be applied to the system at each node and / or on the lines at predefined locations. The scale of the model is 1 kVA for 100 MVA and 400 V for rated voltage of the original system (see Figure 3).

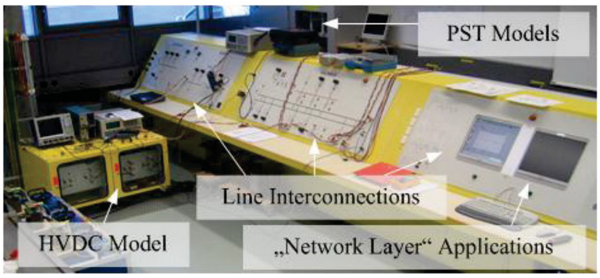


Figure 3: Picture of the laboratory setup

In order to study the impact of all kind of fast network controllers the two power flow controllers (PFCs) have been set up on a UPFC basis [13], [14]. The series voltage capabilities of the UPFC have been designed to be $60\mathrm{V}/\sqrt{3}$ per phase at 7.5 A line current. The following operation modes are available:

- reactive power compensation (shunt source)
- open loop current control (fixed series source)
- closed loop current control (controlled series voltage with P and Q set points)
- Special control software allows the UPFC to operate like a conventional phase shifting transformer since most of the power flow control applications in interconnected power systems are based on this type of device.

In the basic concept of a WAMS the PMUs are placed in substations to allow observation of a part of the power system under any operation condition. For the supervision and control of the network model up to four PMUs have been used. They are integrated in the network model and synchronized by a conventional GPS signal. The data processing is based on the software PSG delivered by ABB [15], [16]. The phasor information is provided to an application and control server, where the control algorithms and general analysis functions are executed (Figure 4).

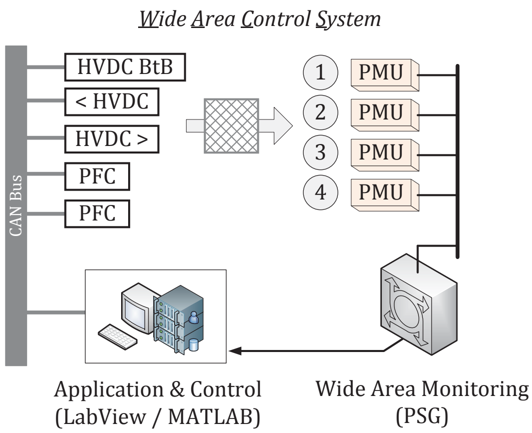


Figure 4: General structure of the wide area control systems

The lab control is realized by LabView software; higher analysis and control applications are utilizing MATLAB environment. The control signals are distributed to the network controllers via a controller area network bus (CAN Bus). For the analysis of the communication with respect to its sensitivity against data transmission errors, the PMU bus structure has been split up into two independent paths. This reflects a more realistic situation of data transmission from remote locations.

3 Application Studies

3.1 State Estimation – Network Layer

PMUs can be utilized to measure phasors in network nodes, which might not be connected to one single SCADA/EMS system. The benefit of having single phasors out of neighboring systems results from a WAMS based long distance corridor supervision without in depth knowledge of the supervised network. Based on such a WAMS setup overall loading information and system state monitoring of transcontinental energy corridors can be realized. On top of this monitoring information the estimation of the state of corridor can be taken as basis for adapting set points of network controllers operating in the corridor or influencing the corridor.

Since state estimation with phasor measurements is not a new approach [17], the background of the state estimation application of a WAMS presented here is the investigation of the general feasibility of such a function. Therefore the focus lies on the application in a real hardware environment rather than on the formulation of a new mathematical approach for state estimation. The basic approach for the system equation is summarizing the voltage and current equations in one single matrix equation (eq. 1).

$$\underbrace{\begin{bmatrix} \boldsymbol{I} \\ \underline{\boldsymbol{Y}}_L \end{bmatrix}}_{\underline{\boldsymbol{H}}} \underline{\boldsymbol{u}} = \underbrace{\left[\underline{\boldsymbol{u}}^{\mathrm{T}}, \underline{\boldsymbol{i}}^{\mathrm{T}}, 0\right]^{\mathrm{T}}}_{\underline{\boldsymbol{m}}} \qquad (1)$$

In this formulation $\underline{\boldsymbol{u}}$ represents the vector of all complex node voltages and $\underline{\boldsymbol{i}}$ represents the vector of all complex line currents. The measurement vector $\underline{\boldsymbol{m}}$ comprises both, line currents and node voltages. The basic algorithm for solving eq. 1 reduces the system matrix $\underline{\boldsymbol{H}}$ and the measurement vector with respect to the measured voltages and currents. I.e. those elements of $\underline{\boldsymbol{m}}$ that are not measured by PMUs are eliminated. $\underline{\boldsymbol{H}}$ will be reduced accordingly. A standard QR factorization algorithm solves the resulting over determined linear matrix equation. Below a certain number of PMU the matrix equation becomes underdetermined. In this case a standard singular value decomposition method has been applied for solving the equations.

Table 1 summarizes the results of representative simulations run for network configuration A for the two cases "*over determined*" and "*under determined*" equations. Figure 2 shows the topology of the investigated system. The four PMUs were located in the nodes Hauterive, Payerne, Schiffenen and Fribourg (instead of Montbovon in order to see the robustness of the approach). In addition to voltages, currents in the lines L7, L5, L1+L2 and L9+L10 were also monitored. The given relative error indicates the deviation from the PMU based estimation to the network calculation with the commercially available power flow software NEPLAN [18].

Table 1: Relative errors in voltages and currents from state estimation with reference to load flow calculation; “E” indicates an estimated value

	Over determined			*Under determined*		
	Δ_{Magn}	Δ_{Angle}	E	Δ_{Magn}	Δ_{Angle}	E
$\underline{U}_{Hau.}$	0.00%	0.00%		0.00%	0.00%	
$\underline{U}_{Mon.}$	0.06%	0.07%	x	0.06%	0.06%	x
$\underline{U}_{Pay.}$	0.00%	0.01%		0.00%	0.00%	
$\underline{U}_{Sch.}$	0.00%	-0.02%		0.14%	-1.17%	x
$\underline{U}_{Fri.}$	0.00%	0.00%		0.11%	-0.70%	x
$\underline{I}_{L7}$	1.54%	-0.54%		0.68%	-0.41%	
$\underline{I}_{L5}$	0.94%	-0.80%		0.94%	-0.81%	x
$\underline{I}_{L4}$	-0.20%	0.34%	x	-0.20%	0.32%	x
$\underline{I}_{L1+L2}$	0.00%	0.00%		0.00%	0.00%	
$\underline{I}_{L6}$	1.05%	0.57%		-1.09%	1.26%	x
$\underline{I}_{L9+L10}$	-0.25%	0.00%	x	-0.16%	0.11%	

All relative errors of the estimated values are below 2% for both, magnitude and angle of the estimated voltages and currents. Those errors increase but remain still acceptable when the configuration is at the limit to become under determined.

3.2 Coordinated control of phase angle regulators (Network Layer) by means of optimal power flow (Economic Layer)

The algorithms for coordinated control of network controllers has been adopted from [19] since this approach shows optimal performance with respect to coordinated controller setpoint settings for steady state load flow determination. For this case network configuration A has been taken as basis. The basic idea is to run an optimal power flow utilizing all setpoint definition of network controllers as controlled variables. The following objective function will be used:

$$f(\mathbf{x},\mathbf{u}) = \sum_i \left(a p_i^{\mathrm{loss}} + b\varepsilon_i + c\eta_i \right) + \sum_i \left(d\left(u_j - u_j^{ref}\right)^2 + e u_j \right) \tag{2}$$

The first part of this function represents the cost of losses and the cost of overload situations. The second sum stands for a description of costs related to voltage variations. The weighting factors a to e are utilized to adjust the importance of each criterion (Table 2).

Table 2: Overview on weighting factors

Factor	Objective
a	minimization of active power losses
b	keeping line loadings below 90%
c	keeping line loadings below 100%
d	minimization of voltage deviations from references
e	keeping bus voltages within acceptable limits

In reference to the proposed TLA this application is an excellent example of how the economic layer and the network layer can be combined. The measurement layer is considered in the lab realization of the coordinated power flow controller approach as well. In the lab environment the PMU deliver the actual loading status of the network. Topology status, network controller status and control objectives are manually pre-adjusted. This models the real application frame, where the operator defines the actual control target. By extracting data from the SCADA system, topology status and PFC status can be derived automatically. Based on these information the setpoint optimization comprises a topology processor, the optimal power flow instance and a module for result verification. In the utilized setup these routines have been realized in MATLAB (Figure 5).

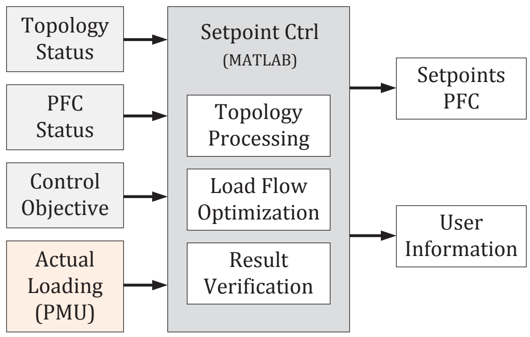


Figure 5: Overall structure of the coordinated control realization as realized in the lab environment

As results of this calculation a new set of setpoints is processed and uploaded to the device controllers. For the sake of simplicity, i.e. to study the impact on the AC network controllers, the HVDC schemes have been disabled (BtB operated in bypass mode). For the basic functionality test, the objective lies on minimizing the network losses while having a balanced voltage profile throughout the system. The weighting factors have been chosen accordingly: $a = 10^6$, $b = 10^3$, $c = 10^5$, $d = 10^4$ and $e = 5 \cdot 10^2$. Figure 6 shows the change in node voltage profile with respect to the bus voltages without optimization. It is obvious that a net increase of the average node voltage is the result out of loss and loading optimization. The loading of the particular lines is decreased in general.

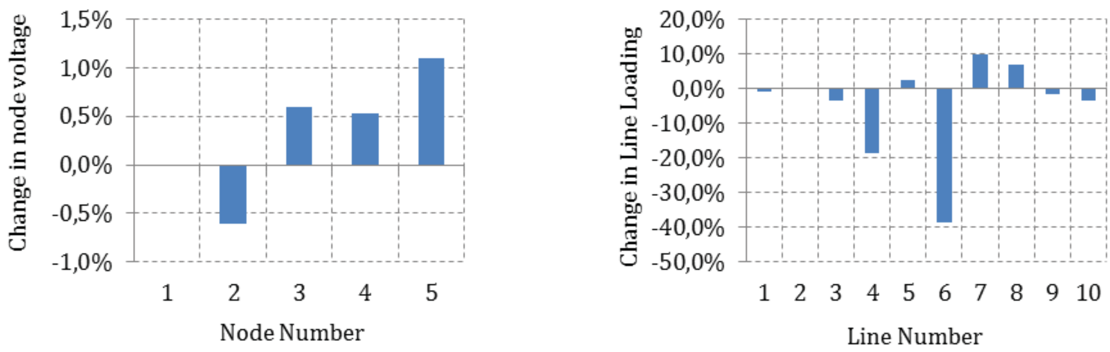


Figure 6: Change in node voltage and line loading as a results of the power flow optimization

The optimization algorithm not only minimizes the loading impact by reactive power flow but also takes advantage of the slack node contribution to the entire load flow pattern. In total an entire loss reduction could be achieved by 1.6%. It should be mentioned that loss reduction could be achieved by a proper selection of weighting factors in the objective function. It can be shown that losses increase for the sake of a more balanced voltage profile.

3.3 Adaptation for Corridor Control with HVDC and ATC Optimization (Economic Layer)

For this analysis network configuration B has been taken in order to analysis a corridor for North-South transmission (see Figure 2). The interconnections to the ENTSO-E grid have been modeled by voltage sources with corresponding internal impedances. Power flow control capabilities have been installed be means of one voltages source converter based HVDC (700 MVA) and two phase-shifting transformers, so that the power flow capability of the corridor between Breite and Sils (Bonaduz) is fully determined. The adjacent network has been modeled by means of an equivalent parallel line. The HVDC control capabilities have been considered in terms of node voltages and provided active as well as reactive power at the receiving end of the scheme. The phase-shifting transformers (PST) are represented by the additional voltage injection capability in the control vector. The constraints for the optimization of equations are defined starting from the evaluation of the branch power flows. With the

HVDC, one adds active and reactive power injections into the network at different places. For the node equations the following constraints have to be added:

$$p_{bus} + p_{load} - p_{gen} + p_{HVDC} = 0 \tag{3}$$

$$q_{bus} + q_{load} - q_{gen} + q_{HVDC} = 0 \tag{4}$$

As for the lines and the PST, we must minimize the active losses. For that, the DC losses have been included in the objective function. The losses of the HVDC scheme have been added as separate constraint according to eq. (5):

$$\Delta p_{converter} = p_{DC,loss} \tag{5}$$

The concept of net transfer capacity (NTC) and available transfer capacity (ATC) is used by the network operators to schedule the network operation and identify congestions in transmission paths. The "day-ahead" determination of the ATC is based on notified and confirmed physical flow one day ahead of operation (see Figure 7).

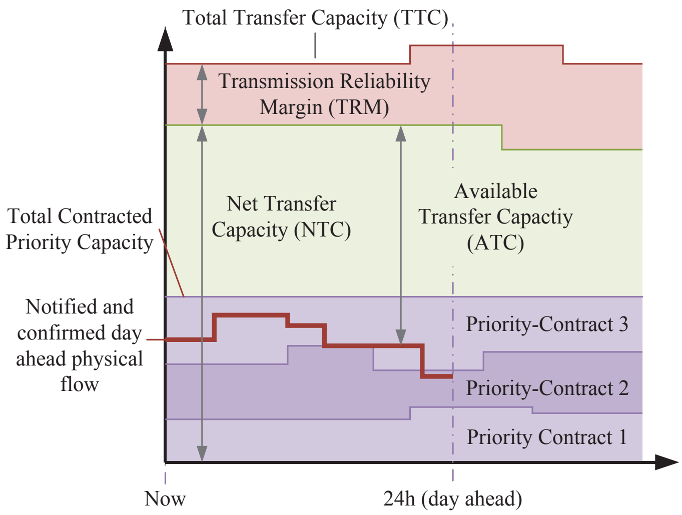


Figure 7: Graphical representation of the definition of ATC according to [19]

For each defined point in time, for example one hour, all the parameters are given in order to be able to organize the daily exchanges of power. When the transaction volumes have been allocated and confirmed, the operator of the network guarantees the transactions and manages physical flows. For most effective network utilization it is beneficial to maximize the ATC.

For this analysis network configuration B has been taken as basis for the ATC optimization. With respect to the day ahead approach of ATC an OPF that determines the setpoints of power flow controllers can help to fulfill this requirement. Therefore the OPF equations need to be extended by an expression that takes the ATC into account [19]. The optimization variables will be extended by a factor λ according to eq. (6):

$$\boldsymbol{x}_{\mathrm{ATC}} = \left[\boldsymbol{x}^{\mathrm{T}}, \lambda\right]^{\mathrm{T}} \; ; \; \lambda \geq 1 \tag{6}$$

The factor λ is used to scale the load at the receiving end of the corridor (Sils). During the case studies it has been shown that λ needs no limitation in the constraints. Hence, the constraints as formulated in eq. (3) and (4) need to be extended with respect to the scaling of the loading at the receiving end of the line:

$$\lambda\left(p_{load} - p_{gen}\right) + p_{bus} + p_{HVDC} = 0 \tag{7}$$

$$\lambda\left(q_{load} - q_{gen}\right) + q_{bus} + q_{HVDC} = 0 \tag{8}$$

It is assumed that the load factor cos (φ) remains constant at those load busses that are subjected to be scaled during ATC calculation. Finally, the objective function needs to be re-written taking into account a fourth term that comprises the nodal load balance at nodes which are relevant for ATC calculation. A new weighting factor g adjusts the importance of this criterion within the objective function:

$$f(\boldsymbol{x},\boldsymbol{u}) = \sum_{\forall ij}\left(a\, p_{loss,ij} + b\,\varepsilon_{ij} + c\,\eta_{ij}\right) + \sum_{i=1}^{n_n}\left(d\left(u_i - u_i^{ref}\right)^2 + e\,u_i\right) + \sum_{\forall kl}\left(f\,\frac{s_{kl}}{s_{\max,kl}}\right) + \sum_{\forall ATCi}\left(g\,\Delta p_{ATCi}\left(\lambda - 1\right)\right) \qquad (9)$$

As simulation scenario a reference loading form January 17th, 2007 at 10:30 has been chosen. The parameter set for the OPF calculation has been adjusted according to earlier studies to: $a = 10^6$, $b = 10^3$, $c = 10^5$, $d = 10^4$, $e = 5 \cdot 10^2$, $f = 0$, $g = 1$.

The first calculation has been performed in order to verify the MATLAB implementation of ATC calculation. Therefore the network model has been implemented into the power system simulation environment NEPLAN [18] and PowerWorld [21]. For the steady state calculation the HVDC scheme has been represented as load / injection model. As indicated in Figure 8 the results are almost equal. The small differences between the results are caused by policies on power measurement and differences in the implementation of the network controllers. With HVDC control, the ATC increases considerably. This is quite natural since new transmission capacity is added. With all the PST used, the limits of existing lines are reached. In a second simulation run it has been investigated how precise the online calculation of the ATC appears to be. For this purpose the base case scenario has been setup with the analogue simulator. For this case the power that is injected into the Sils node (P_{Sils}) almost remains the same for all controller actions when the load is assumed to be constant for each simulation run. By activating the ATC optimization for the different power flow controlling devices the ATC increases (see Figure 8).

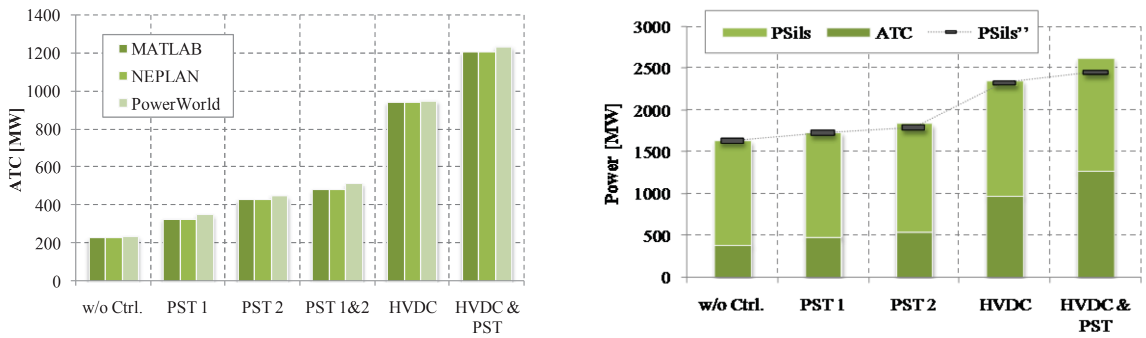


Figure 8: Results of ATC calculations with different tools (left) and Increase of ATC by means of power flow control and comparison to “measured” ATC (right)

In order to validate the proposed ATC calculation, the loading in the Sils node has been increased until one of the transmission devices was reaching its operational limits (P_{Sils}”). This equals an experimental determination of ATC. Only very small differences between the calculated the measured ATC could be achieved. When the resistive load is increased, the voltage at the Sils node will decrease. This effect distorts the calculation of ATC.

3.4 Detection of power oscillations (Network Layer)

One approach to detect power oscillations by means of wide area measurement is based on Kalman Filter techniques and has been outlined in [22]. The key problem is the on-line detection of dangerous electromechanical oscillations in power systems using dynamic data such as currents, voltages and angle differences across a transmission line. They can be provided by PMUs. The collected measured data are evaluated with the objective to estimate dominant frequency and damping during normal operation of the power system. The power system is assumed to be affected by disturbances around a nominal operating point. Evaluation of the estimated model parameters enables quantitative detection of oscillations and other properties of the system, such as actual system stability. The advantage of the laboratory environment is to excite power oscillations under controlled conditions. In general there are two options to model power oscillations:

- Tune the controllers in the system and arrange the system topology to excite oscillations after a pre-defined disturbance.
- Modulate the signal of the torque control at one of the generators in the system – supposing that the generators are driven by controlled machines.

For this study the second option has been taken since the frequency of the oscillations can be directly adjusted by the torque control of the system. Network configuration A has been taken as basis for this analysis. A complex mathematical model of laboratory system for tuning purposes is not needed in this case. The set point of the torque control of a generator set at Schiffenen has been modulated to force a power oscillation in the typical frequency range below 2 Hz. The basic algorithm of the applied WAMS for oscillation detection is based on eigenvalue analysis. Oscillations are characterized by complex eigenvalues. The real part α_i gives the information about the decay rate and the imaginary part

$$\omega_i = 2\pi f_i \tag{10}$$

about the frequency f_i [Hz] of the oscillatory mode. In practice, a good measure for damping seems to be the damping ratio defined for each eigenvalue as:

$$\xi_i = 100 \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \omega_i^2}} \% \tag{11}$$

In this application the most relevant oscillations to detect is the dominant one; i.e. the one corresponding to the complex poles having the biggest real part among all others. In a regular power system they usually satisfy the following expression:

$$\begin{aligned} \xi_i &< 10\% \\ f_i &< 2Hz \end{aligned} \tag{12}$$

If a negative (or a very small positive) damping can be detected in supervised grid, it indicates the system is becoming unstable. This is very important information about the entire power system. In the applied WAMS system this event can be signalized by an alarm to the operator. The study has been carried out at the system shown in Figure 2 where the lines L1+L2 and L5 have been switched off and the PAR was by-passed. To collect data, one PMU has been installed in node Schiffenen. Figure 9 shows one representative result of the measurement series that has been performed in the lab. The measured voltage indicates the power oscillation that has been modeled as outlined above. After a short analysis time (T_0) the WAMS provides an output signal indicating the damping and the frequency of the detected power oscillation. The damping is in the range of 10%, the frequency has been estimated to be in the range of 1.9 Hz which is inline with the modulated torque control signal.

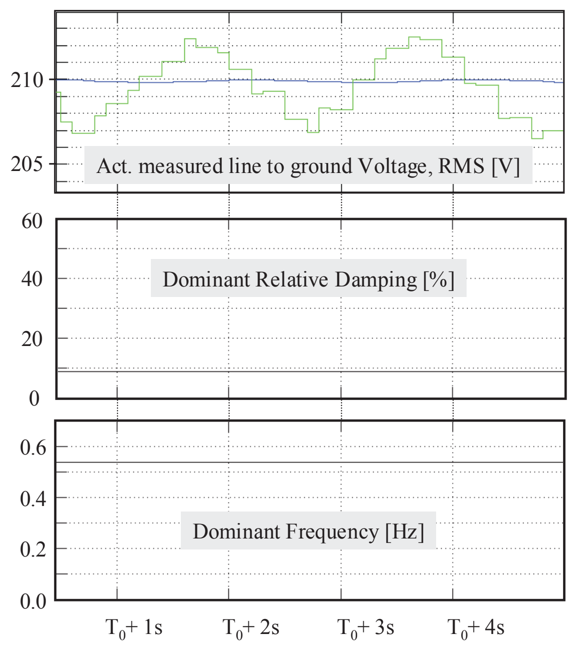


Figure 9: Results of oscillation damping test

3.5 Power oscillation damping with embedded HVDC (Network Layer)

The concept of embedded HVDC allows handling a HVDC scheme like a “regular” network controller for e.g. power oscillation damping purposes. The objective of the case study presented here is to show the basic functionality of such a setup in a lab environment utilizing measurement signals from PMUs based on the network configuration A. The basic setup of the studied configuration is shown in Figure 10. In this configuration the most simple control system configuration has been chosen – a PI control structure. The parameters have been tuned according to the network representation as shown in Figure 10. The advantage of the lab environment is to excite power oscillations under controlled conditions. In general there are two options to model power oscillations:

- Tune the controllers in the system and arrange the system topology to excite oscillations after a pre-defined disturbance.
- Modulate the signal of the torque control at one of the generators in the system – supposing that the generators are driven by controlled machines.

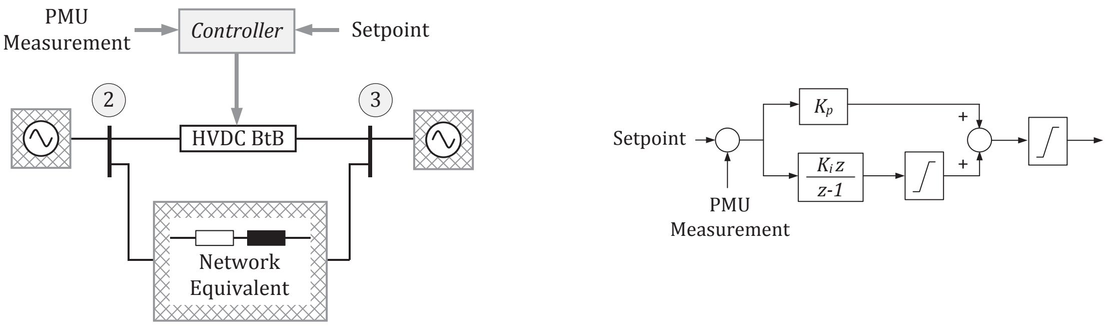


Figure 10: General system equivalent for the application of a damping controller for the HVDC scheme and simple control structure utilized for damping control of the HVDC scheme

For this study the second option has been taken since the frequency of the oscillations can be directly adjusted by the torque control of the system. A complex mathematical model of laboratory system for tuning purposes is not needed in this case. The monitoring of power oscillations by WAMS provides the input signal for damping control. Due to the time delay in data transmission and processing the corresponding input signal is subjected to some minor deficiencies as shown in Figure 11. With some appropriate signal rehashing this power flow measurement signal is suitable enough to be used for damping control purposes. Even though the most simple control system setup has been used for the damping control realization the magnitude of the power oscillation between node 2 and 3 can significantly be reduced. The investigated scenario comprises a regular setpoint control mode of the DC scheme. After approximately 2 min of normal operation the power oscillations are excited (3 min). Then the damping control becomes active for around the same amount of time (Figure 11).

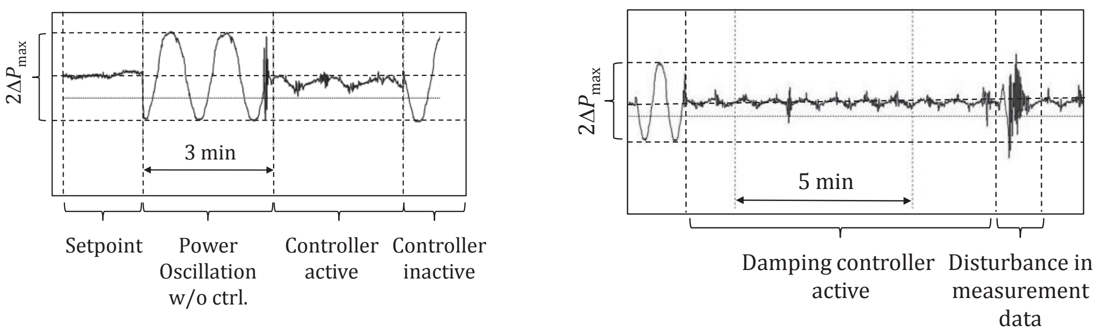
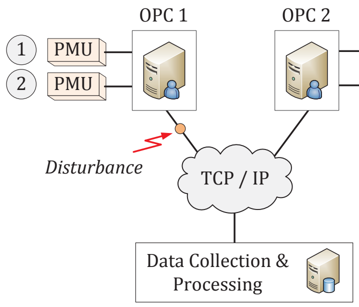


Figure 11: Power flow from node 2 to 3 with and without damping control (left) and impact of artificial disturbances in data transmission

In a second simulation run, certain disturbances on the measurement layer occurred. The resulting bad quality of input signals for the control system leads to major disturbances in the power flow of the line. These disturbances are almost of same magnitude then the original power oscillations to be damped (Figure 11). Technically the system with PMUs enables to detect the status of the electrical grid in real-time. Therefore, the loading condition, stability and disturbances can be detected to further optimize the existing transmission lines and prevent critical situations.

3.6 Impact of the Sensitivity of the Communication System (Measurement Layer)

Dedicated data supervision has not been applied in this application study. Nevertheless, this tremendous impact shows the importance of input data quality and motivates a sensitivity analysis of the communication system. Sensitivity of the communication system against disturbances in the data communication system is considered as key factor for the quality of the overall control system. As shown in the second case study, system behavior can turn out to be even worse when utilizing faulty input signals. When generalizing the setup of a wide area communication system at least two different OPC servers are processing data from (remote) locations. Consequently, the question is: *How will a disturbance on the data channel (from one of the OPC servers to the processing unit) impact the quality of PMU based system wide control ?* In order to investigate this representative scenario the four PMUs have been connected to two different OPC servers. Each OPC server is connected by means of TCP/IP to the central data collection and processing unit. One of the data channels is subjected to typical disturbances (**Figure** 12).



Angle difference between node 2 and node 4 as reference for the evaluation:

$$\Delta\delta^{ref} = \frac{1}{\Delta T}\int_{T_0}^{T_0+\Delta T} \delta_4(t)-\delta_2(t)\,dt \quad \text{with} \quad \delta_i(t): \underline{u}_i(t)=u_i(t)e^{j\delta_i(t)}$$

Figure 12: System setup for the investigation of disturbances in the measurement layer

The time critical information is the angle information of voltages and currents at the PMU location. Therefore, the angle signal has been utilized as reference to evaluate the impact of disturbances. As reference serves the angle difference between node 2 and node 4. Four typical disturbances in a packet switching network have been investigated. “Delay” a determined packet delay. “Jitter” considers a “Delay” plus a random delay for each packet in a defined time interval. “Package loss” described the probability of loosing a packet during the transmission. Finally the “Reduced bandwidth” criterion describes the effect of data channel overload resulting in a bandwidth reduction for data transmission (Figure 13). The result of the communication system analysis shows measurement errors below 4% except for the “extreme” situations of 500ms packet delay, a huge Jitter and abnormally low bandwidth limitation.

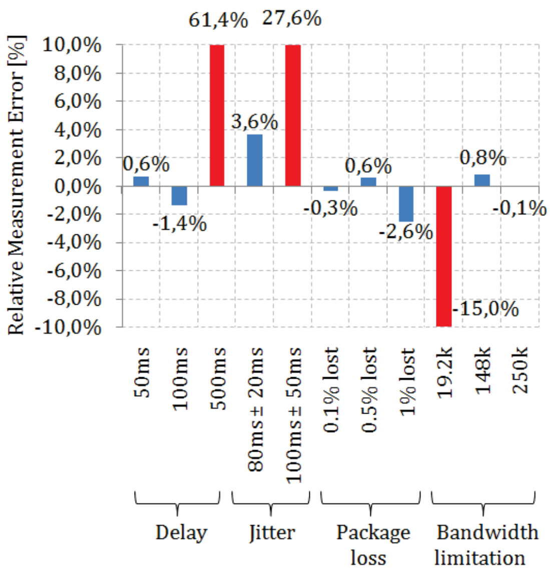


Figure 13: Relative measurement error for certain disturbances in data transmission within the measurement layer

4 Summary and Conclusion

Wide area monitoring and control utilizing phasor measurement units have become state of the art for the next generation of power system SCADA and energy management systems, which allows for more in-depth real-time analysis of the system operation. This paper summarizes a series of application studies of WAMS and WACS within a real-time environment that represents a part of the Swiss transmission grid comprising different network controllers from the FACTS devices and HVDC family. All functions have been arranged around a three layer architecture where all instances that affect the power system operation have been considered at the same time.

The application studies demonstrate the practical applicability of WAMS and WACS for transmissions system operation not only as protection system but also as enabler for the coordinated optimization and operation of various power flow controlling devices in a transmission grid. With the real-time environment dedicated results for the role of the communication systems could be obtained.

With the work presented in this paper a foundation has been set for further investigations on how WAMS / WACS systems can improve the operational behavior of transmission grids. Further work must be directed towards an active integration of other network control functions in the overall approach and redundancy provision within the grid as well as in the telecommunication system. With respect to the upcoming challenges of bulk power transmission with infeed from huge renewable energy plants it can be expected that the WAMS / WACS technology will become a cornerstone in the realization of flexible and secure future overlay grid functions.

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